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STATISTICAL PERFORMANCE OF TOPEX/POSEIDON PRIME MISSION GROUND AND ON-BOARD EPHEMERIDES AND CONSEQUENCES FOR THE EXTENDED MISSION

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Statistical Performance of TOPEX/POSEIDON Prime Mission Ground and On-Board Ephemerides and Consequences for the Extended Mission*

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ABSTRACT

TOPEX/POSEIDON is a joint American/French ocean topography experiment currently in the last year of its nominal mission and soon to enter a three year extended mission. To meet science requirements, the satellite must point the altimeter antenna at the ocean local nadir with good accuracy, This paper discusses the pointing accuracy of the Operational Orbit Ephemeris and its Fourier power series representation in the On-Board Computer. The consequences for the extended mission due to this performance are also discussed.

L Introduction

TOPEX/POSEIDON is a joint American/French ocean topography experiment conducted by the National Aeronautics and Space Administration (NASA) and the Centre National d'Etudes Spatiale (CNES). It was launched by an Ariane launch vehicle on August 10, 1992 to study and map ocean circulation and its interaction with the atmosphere, to improve our knowledge of climate changes and heat transport in the ocean, and to study the marine gravity field. These objectives are accomplished through accurate mapping of the ocean surface with a dual-frequency on-board radar altimeter and precision orbit determination. The satellite is currently in the last year of its three year nominal mission and will then enter a three year extended mission.

To meet science requirements and constraints, the TOPEX/'POSEIDON satellite must point the altimeter antenna at the ocean local nadir with good accuracy. It must also point an articulated high gain antenna at the NASA Tracking and Data Relay Satellite System (TDRSS) to allow communication and tracking for Operational Orbit Determination (OOD). This requires real-time on-board knowledge of the satellite and TDRSS ephemerides. This paper will discuss only the satellite ephemeris.

The 00D is the responsibility of the Goddard Space Flight Center/Flight Dynamics Facility (GSFC/FDF). Using tracking data from TDRSS, GSFC/FDF produces satellite state vectors for transmission to the TOPEX/POSEIDON Navigation Team at JPL for use as initial conditions for propagating the Operational Orbit Ephemeris (OOE). The On-Board Computer (OBC) ephemeris commands load consists of a Fourier Power Series (FPS) representation of the 00E. Reference (1) indicates that the

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overall pointing error requirement (half-cone angle) is 0.07 degrees (1-o). Portions of this overall error have been allocated to the OOE generation and the OBC ephemeris representation process. A 0.015 degree (1-σ) pointing error is allocated to errors in ephemeris prediction over a seven day prediction period due to 00D and 00E generation. A 0.022 degree (1-o) pointing error is allocated to FPS representation of the OBC ephemeris over a 10 day span. Figure (1) defines the nadir pointing error and shows the relationship between it and the along-track position error.

IL 00E Statistic! Performance

Currently, the GSFC/FDF supplied state vectors are provided three times a week and have epochs at the start of the tracking arc, at the end of the tracking arc (seven days, ten hours past the start), and seven days after the end of the tracking arc. The first state vector is used as an initial condition for 00E propagation. Comparisons between the 00E and the remaining GSFC/FDF state vectors are made to ensure compatibility between DPTRAJ and the GSFC/FDF software. Because the 00E includes a definitive data set, from the start to the end of the tracking arc, and a predicted portion after the end of the tracking arc, a comparison between the previous week's prediction and the current week's definitive data can be made to determine the performance of the prediction software. The difference between the predicted nadir pointing angle and the actual nadir pointing angle may be no greater than 0.015 degree (1 -σ) after seven days.

The OOE is generated from GSFC/FDF supplied state vectors using the Double Precision Trajectory System program (DPTRAJ). DPTRAJ force models include[(2)]:

- Geopotential Model

  The model used for mission support is a slightly refined version of the GEM-T3, referred to as the Joint Gravity Model JGM-2, which models the Earth's geopotential to degree and order 70. Due to computational limitations, a truncated 20x20 version is used in DPTRAJ.

- Luni-Solar Gravity

  Both the Sun and Moon are considered point masses.

- Solid Earth Tides Model

  This model compensates for the deformation of the solid portion of the Earth induced by the tidal effects of the Sun and Moon.

- Atmospheric Drag

  Drag is modeled as a function of atmospheric density and satellite velocity relative to the atmosphere. Density is computed using the Jacchia-Roberts model and solar and geomagnetic activity data supplied by National Oceanic and Atmospheric Administration (NOAA).

- Solar Radiation Pressure

  To match GSFC/FDF software, DPTRAJ uses a conical shadowing model that does not allow integrator restarts upon entry and exit from the "Earths' shadew.

- Variable Mean Area

  The variable mean area model allows for variable satellite cross-sectional area as a function of steering mode for computing perturbations due to atmospheric drag and solar radiation pressure,

- Anomalous Force

  Shortly after launch, orbit trend analysis indicated the presence of body-fixed along-track forces comparable to drag. Plans with GSFC/FDF were made to estimate an along-track thrust τ, where the along-track thrust is measured in $(1 + \tau)$ micro Newtons.

The performance of the 00E is investigated in three regions: the nominal sequences in which no satellite maneuvers, except for standard yaw steering, are performed, during periods when yaw mode transition maneuvers and yaw flip maneuvers are performed, and during periods after propulsive maneuvers are performed.

Figure 2 shows the performance during the nominal sequences from the first Orbit Maintenance Maneuver (OMM), OMM1, through 0MM8 + 1548 hours. The figure shows the maximum and minimum errors, the mean error, and the mean error plus and minus one σ as a function of prediction time. The maximum error after seven days approaches 0.008 degrees but the mean error is significantly less, below 0.003 degrees after seven days which is well under the 1-σ limit of 0.015 degrees

Yaw mode transition occur at low β' angles, defined as the angle between the earth-sun vector and the projection of the vector onto the orbit plane. These maneuvers are in three forms: a switch from sinusoidal yaw steering of the satellite to fixed yaw steering (S->F), a 180 degree yaw flip maneuver (YF), and a switch from fixed yaw steering to sinusoidal yaw steering (F-> S). The yaw flip takes place at β' = O degrees while the S->F and F->S transitions typically occur at $\pm$ 15 degrees. The performance during these periods is generally quite different than during the nominal sequences. Figure 3 shows the performance of each sequence during which yaw mode transitions took place between 0MM3 and OMM4. Three basic styles of curves can be seen. Generally, the S->F transitions show the lowest pointing errors while the F->S transitions show the largest errors, sometimes reaching three times the mean nominal error. The YF transition curves show convex behavior. These differences may be due the tracking arc being restarted at each yaw mode transition. The shorter arc length used in the OOD fit can amount to a larger error in the propagation. The behavior of the YF curves may be due to the errors induced by comparing two data sets with short arc lengths as well as slight differences between trajectory propagators.

There have been eight propulsive orbit maintenance maneuvers to date to keep the satellite ground track within the required bounds. After such a maneuver, state vectors are supplied daily until the seven day, ten hour tracking arc is complete. Figure 4 shows the pointing accuracy after 0MM7 that each state vector brings. While the accuracy of the 40 hour solution is worse than that of the 16 hour solution, the general trend of increasing accuracy as a function of tracking data arc length is shown.

111. **Performance of the OBC Ephemeris Load**

As a Multimission Modular Spacecraft (MMS), TOPEX/POSEIDON has inherited the LANDSAT ephemeris representation concept of compressing the predicted ephemeris in a FPS and On-Board ephemeris reconstruction algorithms. The following modeling design assumptions have been adopted(3):

1 A 42-coefficient FPS is used for each of the six Cartesian state vector components.

2 The time span of the OBC ephemeris load is 10 days and is uplinked weekly in routine operations.

3 A grid spacing of 10 minutes is used for the linear least squares fit of the FPS coefficients and the OBC recovers the ephemeris at these grid points.

4 The residuals of the fit are computed and uploaded to the OBC for a 30 hour span giving increased accuracy over this limited span.

5 Two frequencies are included in the FPS, the satellite mean orbital frequency and the earth sidereal frequency.

6 The satellite mean orbital frequency is calculated form the mean semi-major axis .

7 A four point Hermite interpolation formula is used by the OBC to compute the position and velocity of the satellite at the request time.

Prior to the fourth orbit maintenance maneuver, three ephemerides, in addition to the standard weekly ephemeris, were generated to avoid large deviations of the post burn trajectory. These ephemeris loads were: a Predicted Post Burn (PPB) ephemeris based on the nominal maneuver design and uplinked as part of the maneuver block, a PPB ephemeris which was based on a maneuver tweak, and a no-maneuver ephemeris which is uplinked in case of no execution of the maneuver. Reference (4) suggested a strategy, later adopted, to build a single load based upon the nominal maneuver design (without the tweak). This simplified the work for the flight team and standardized plans around the maneuvers. In both cases, the performance of the PPB ephemeris depends on how closely the predicted burn matches the actual bum,

Figure 5 shows the pointing accuracy for two representative sequences during the period from OMM7 to OMM8. The errors are well below the maximum allowed 1-σ error of **0.022** degrees. The FPS representation is very stable and these two cases are similar to the other cases between OMM 1 and OMM8. For the entire period of OMM7 to 0MM8, the maximum pointing error was **0.0072 ± 0.0008** degrees with the largest error at 0,0085 degrees.

IV. Consequences for the Extended Mission

The performances of both the OOE and the OBC ephemeris load have been good. The one week OOE prediction and the ten day FPS representation errors fall well below the 1-σ accuracy required, especially during the nominal sequences. This suggests that the length of the 00E and OBC ephemeris may be extended without exceeding the required error tolerance. These studies, discussed below, show that the span of 00E may be doubled to 14 days and the span of the OBC Ephemeris Load doubled to 20 days without reaching the error limits.

The data required to study the 14 day OOE were not available for each period between OMMs. Therefore, two periods were chosen for analysis. The period from 0MM5 to OMM6 was chosen because it contains a nominal sequence with a large (0.007 degrees) pointing error after 7 days. The period from 0MM7 to OMM8 was chosen because it covered a large period of time, approximately seven months, and would therefore have a greater number of sequences for study. Figures 6 and 7 compare the one and two week performances during the period from OMM5 to OMM6 for the nominal sequences and the yaw mode transition periods respectively. The maximum error during the nominal sequences does not appreciably change when going from a "J day to a 14 day prediction. The maximum error of 0.007 degrees shown in the 7 day prediction occurs during a sequence that occurs after a F->S transition. When this sequence is analyzed for its 14 day performance, it is therefore included in a yaw mode transition period instead of in a nominal sequence time span. The 14 day performance during the yaw maneuvers does increase significantly, reaching 0.01 degrees after 10 days of prediction. Data were not available for analysis of a longer span in many cases. It can be seen that the 14 day behavior is even more unpredictable than the 7 day behavior. For instance, some curves decrease to small errors prior to 7 days only to significantly increase afterwards.

Figures 8 and 9 compare the one and two week performances during the period from 0MM7 to 0MM8 for the nominal sequences and the yaw mode transition periods respectively. In this case, the maximum error after 14 days is approximately three times the maximum error after 7 days. These errors are, however, consistent with those from 0MM5 to 0MM6. Likewise, the maximum error during the yaw maneuver sequences show errors close to 0.01 degrees after 10 days.

The analysis of the nominal sequences indicates that increasing the prediction time from 7 days to 10 days will not cause pointing errors to exceed the maximum allowed. However, the high errors over a time span of less than 14 days during the sequences with yaw maneuvers suggest that, given the generally more unpredictable nature of the performance during yaw maneuver times, it might be possible to exceed 0.015 degrees after 14 days. The best strategy might be to use a 14 day prediction during the nominal sequences and revert back to the 7 day prediction during yaw maneuver times.

The 20 day OBC ephemeris load is much more stable than the 00E. At the TOPEX/POSEIDON altitude, drag does not significantly degrade the ability of the FPS to fit the data(5). The maximum pointing error for a 20 day fit over the period from OMM7 to 0MM8 is 0.013 degrees while the mean maximum error is 0.0076* 0.0016 degrees. Figure 10 shows two examples of a 20 day fit for the same two sequences shown in Figure 5. These representative curves illustrate no differences in the nature of the 10 day fit versus the 20 day fit. This study has also shown that adjustments to the FPS coefficient scale factors do not need to be made. The same scale factors can be used for the 20 day fit that are being currently used for the 10 day fit,

Based on this study, a proposal to decrease the frequency of the OBC ephemeris load uplink from one week to two weeks during the nominal sequences will be made to the TOPEX/POSEIDON project, During sequences with steering mode transitions or yaw flips, the 00E will be calculated weekly And the OBC ephemeris load will be uplinked weekly. This will reduce the level of support required from mission operations while still maintaining acceptable satellite pointing accuracy.

Acknowledgments

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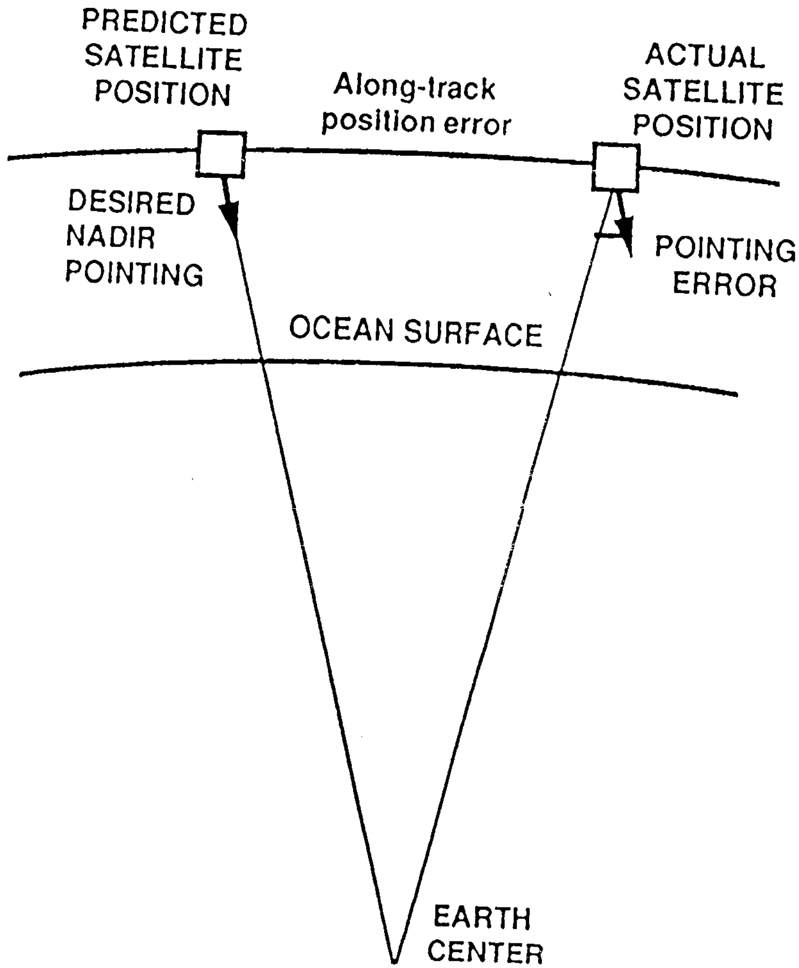


Pointing error (d09)	1σ Along-track position error (km)	3σ Along-track position error (km)
0	0	0
0.015	2.01952048	6.05856143
0.022	2.96196337	8.8858901
0.1	13.463469	40.3904095
0.2	26.9269397	80.7808191
0.3	40.3904095	121.171229
0.4	53.8538794	161.661688

Figure 1. Nadir Pointing Geometry

Figure 2. OOE Pointing Accuracy During Nominal Sequences (OMM1 to OMM8 + 1548 Hours)

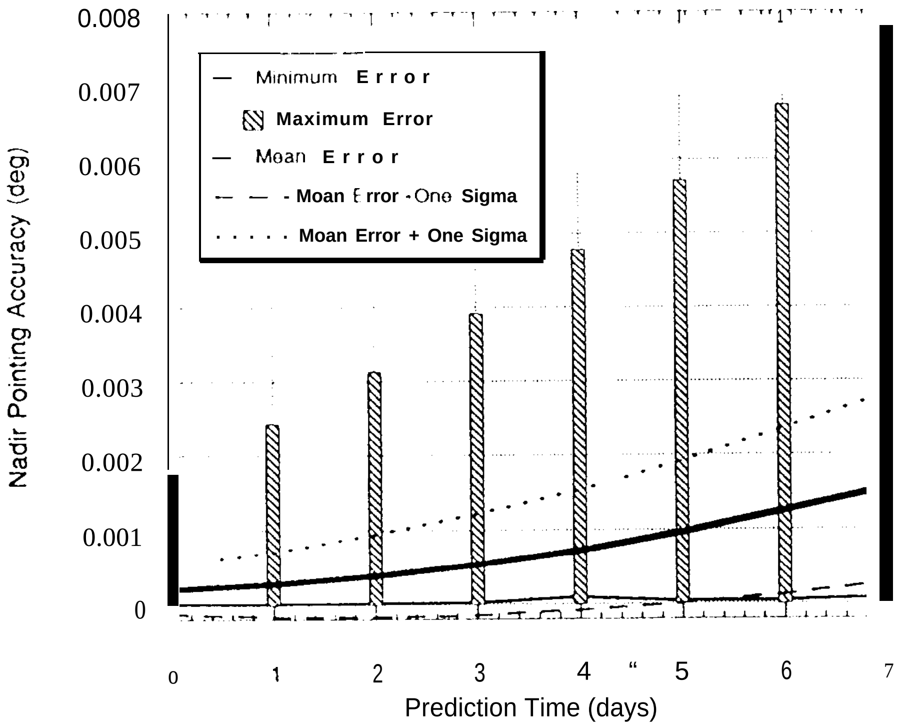


Figure 3. 00E Pointing Accuracy During Yaw Mode Transitions (OMM3 to 0MM4)

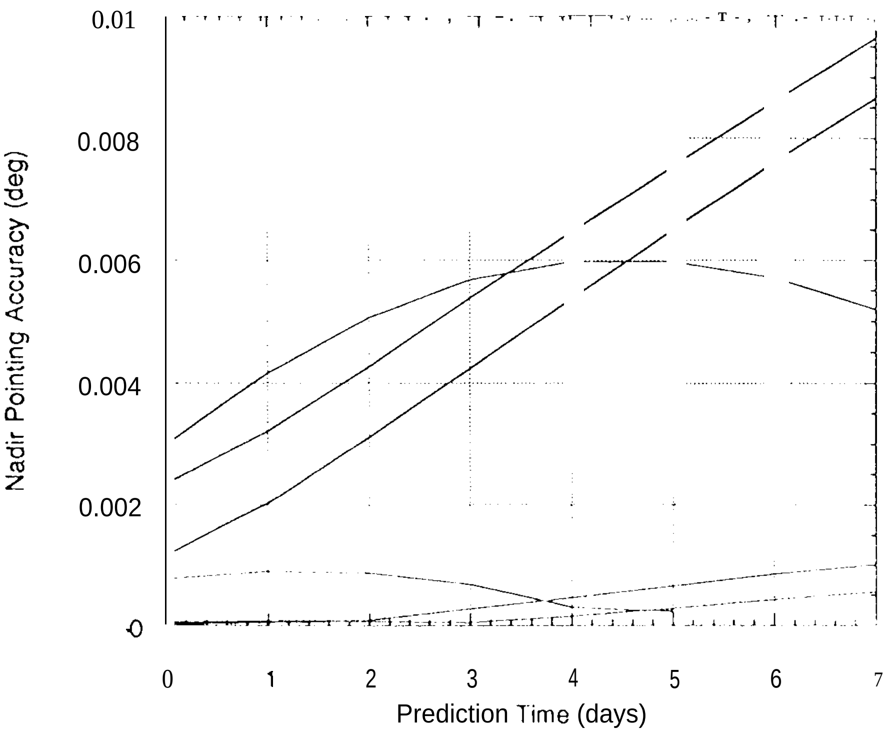


Figure 4. OOE Pointing Accuracy
Immediately After OMM7

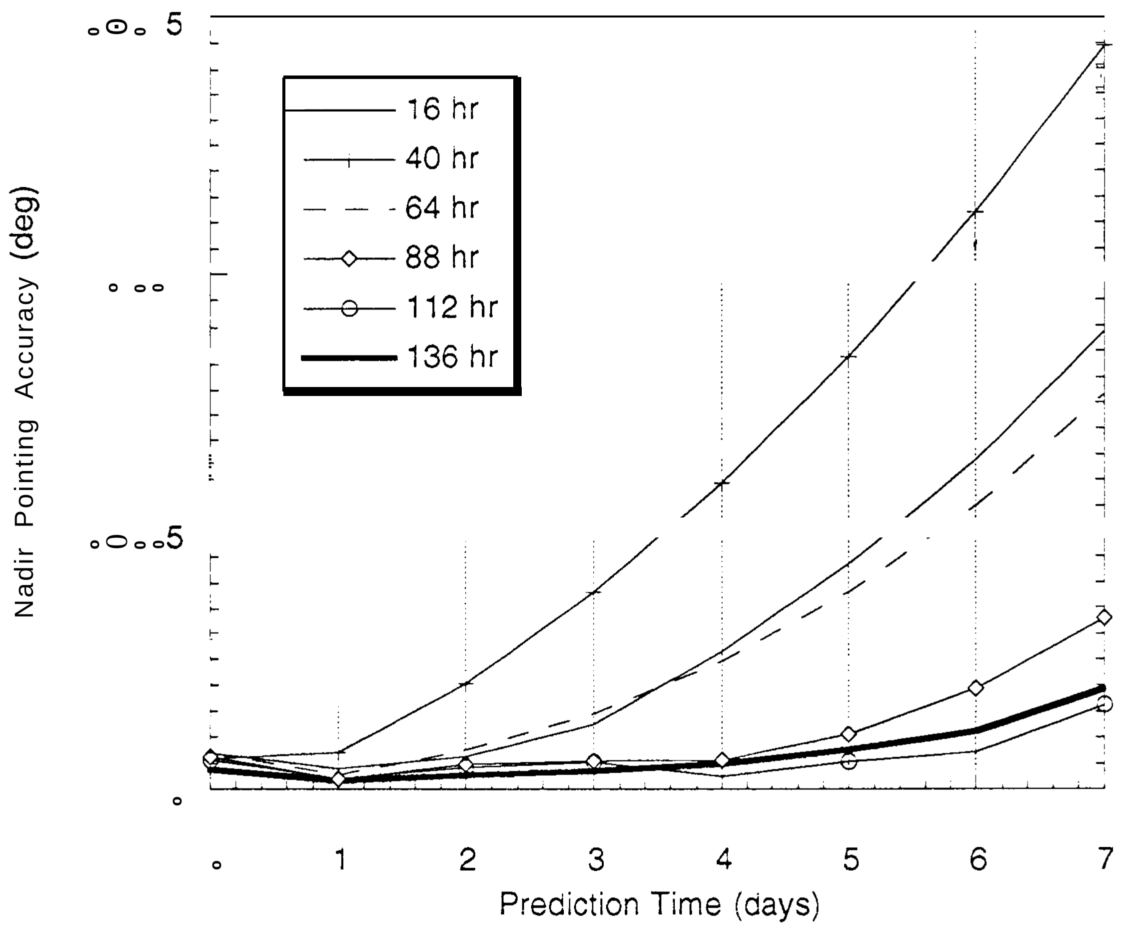
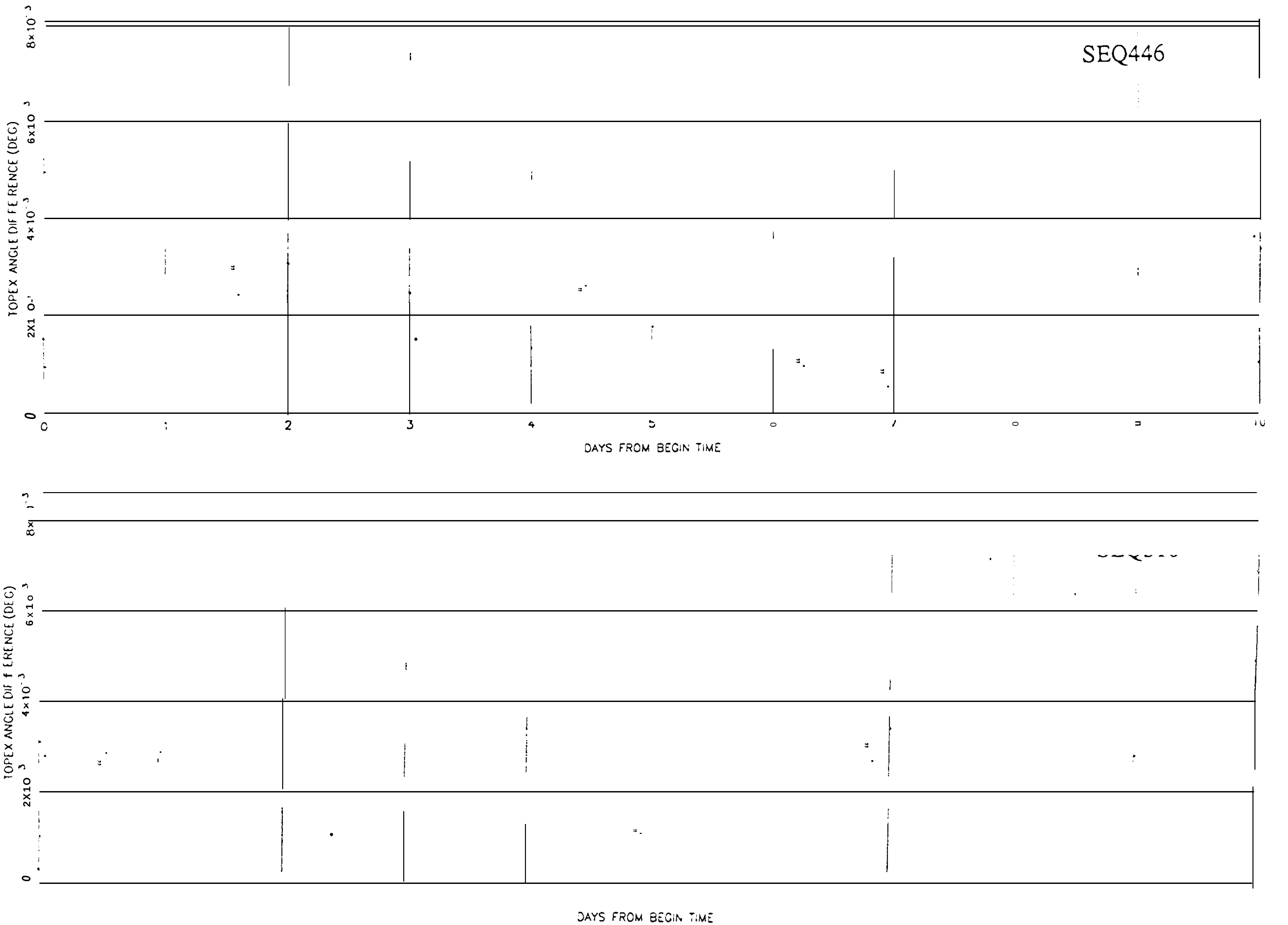
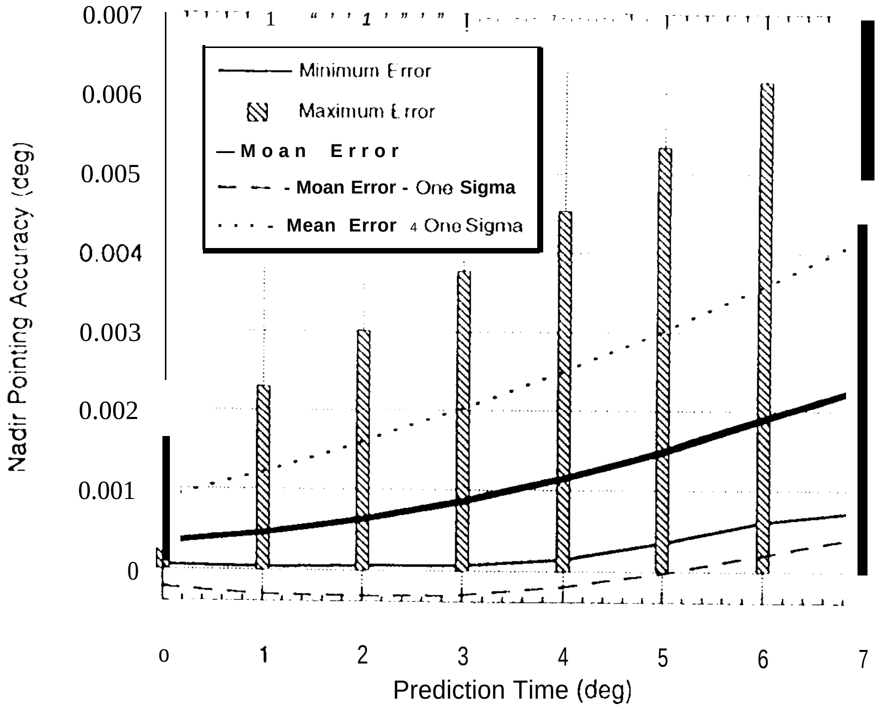


Figure 5. OBC Ephemeris Load Pointing Accuracy





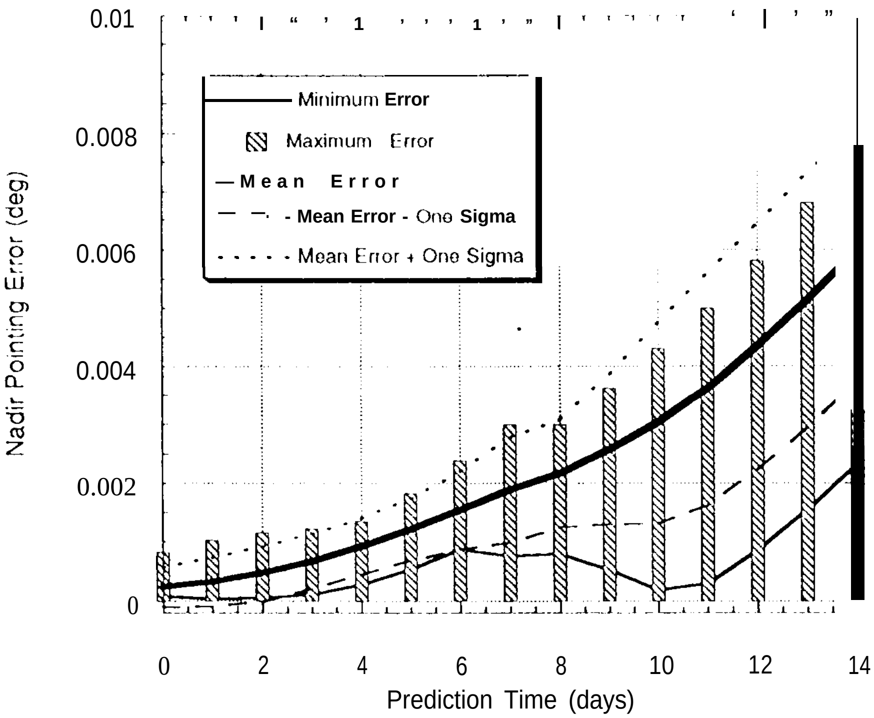
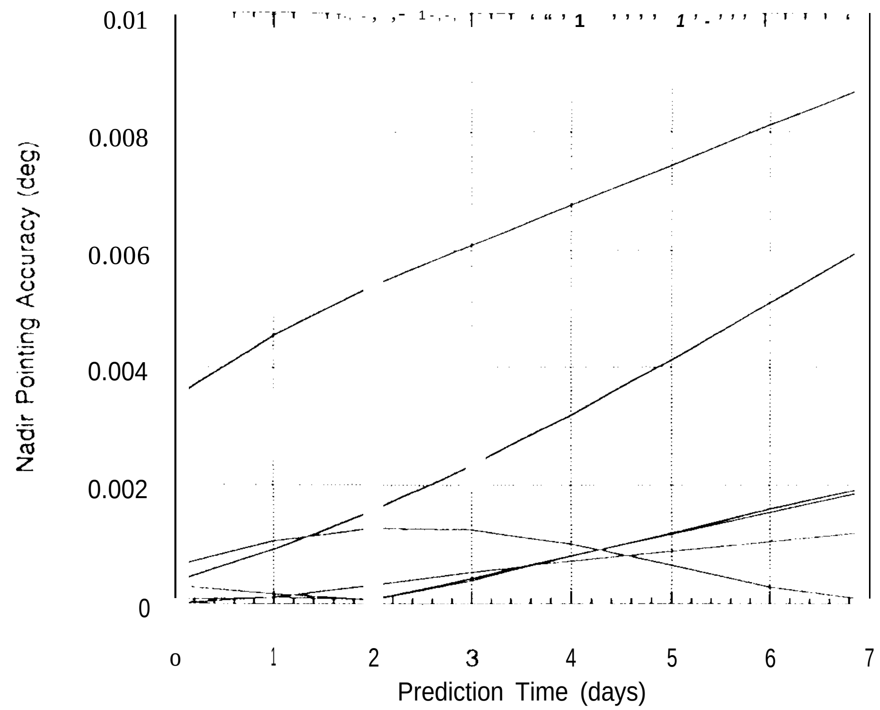


Figure 6. Comparisons of 7 Day and 14 Day OOE Pointing Accuracy During Nominal Sequences (OMM5 to OMM6)



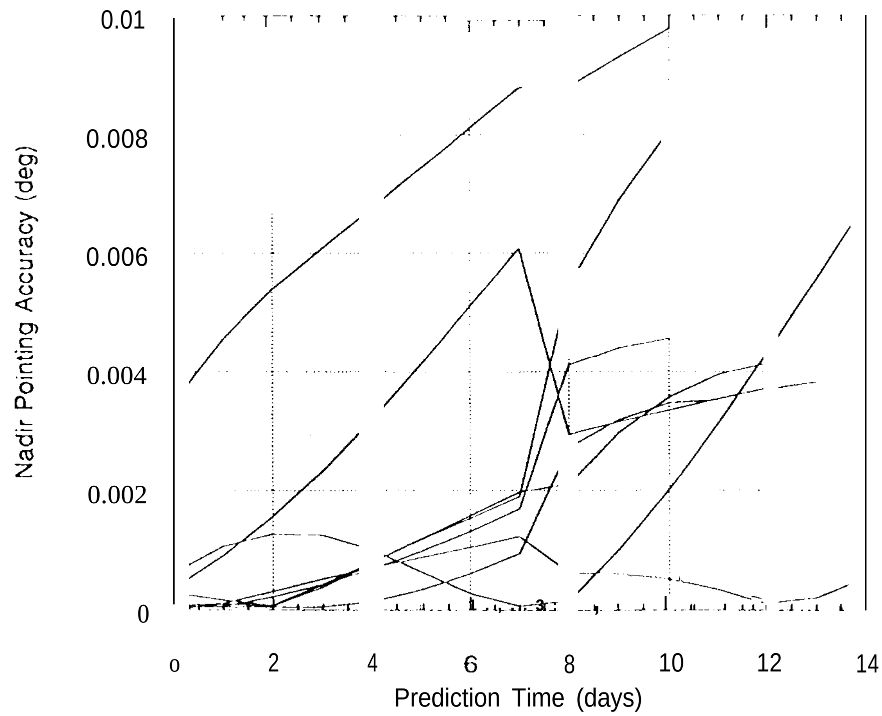


Figure 7. Comparisons of 7 Day and 14 Day 00E Pointing Accuracy During Yaw Mode Transition Sequences (OMM5 to 0MM6)

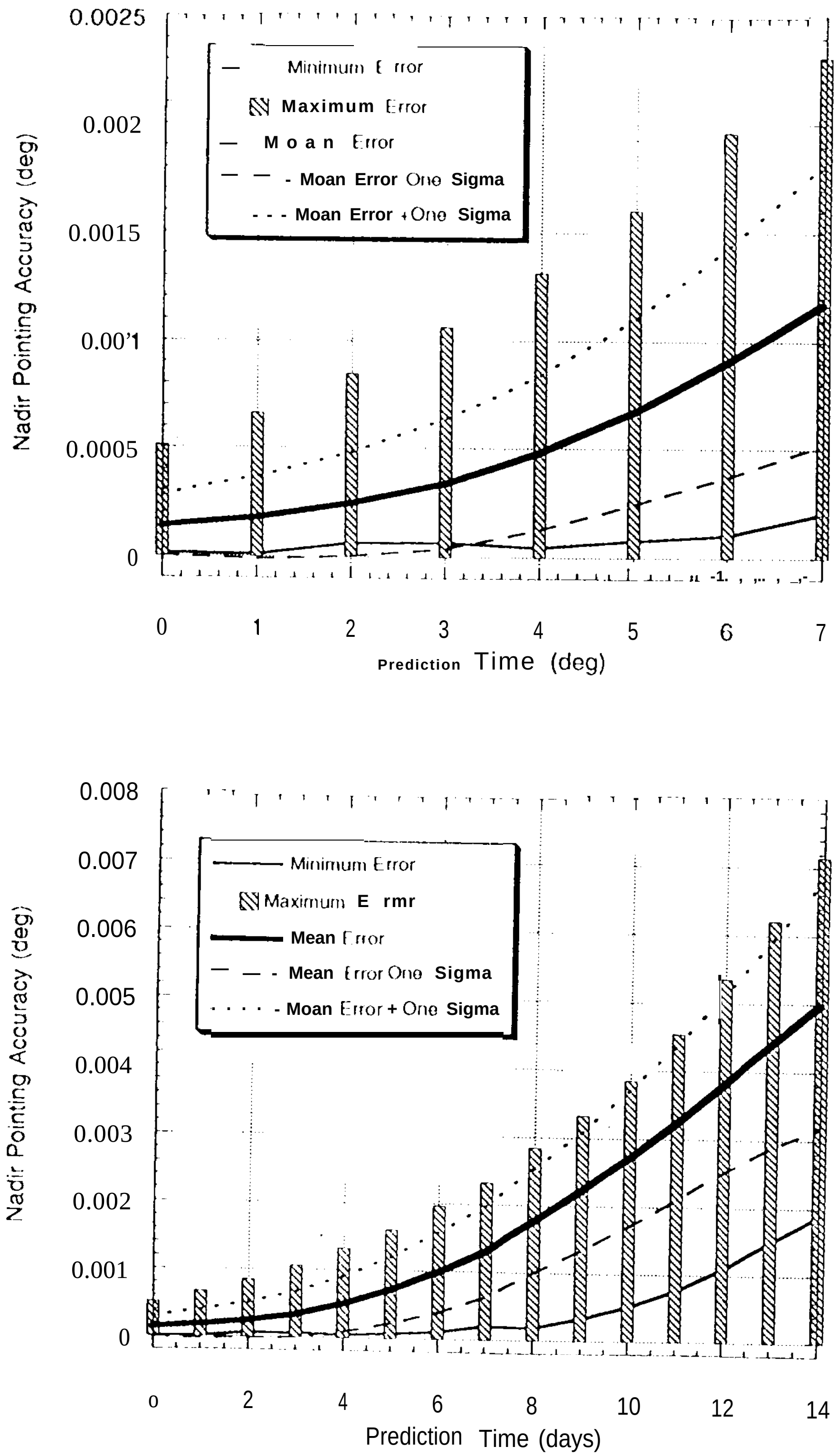


Figure 8. Comparisons of 7 Day and 14 Day OOE Pointing Accuracy During Nominal Sequences (OMM7 to 0MM8)

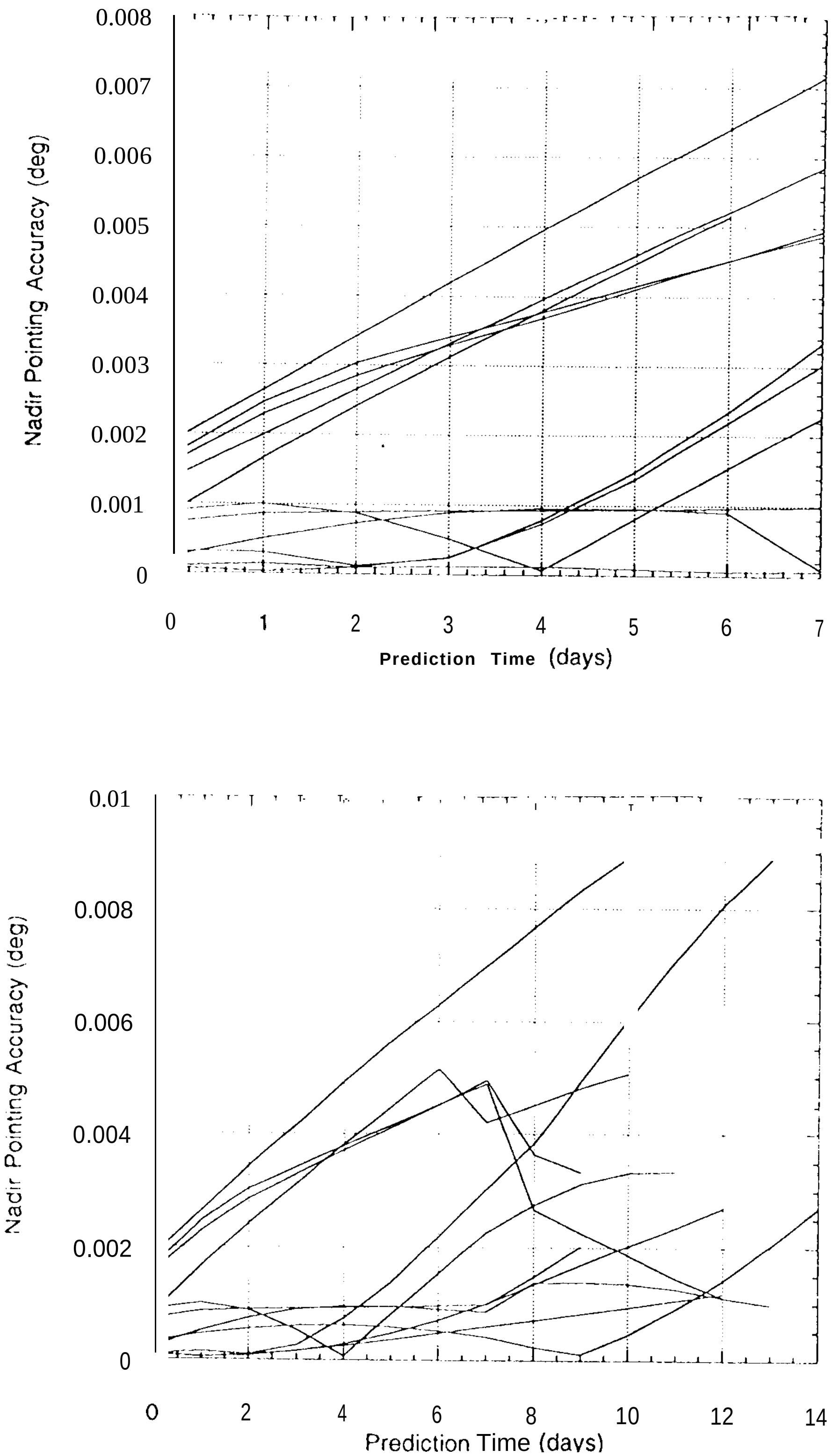


Figure 9. Comparisons of 7 Day and 14 Day 00E Pointing Accuracy During Yaw Mode Transition Sequences (OMM7 to 0MM8)

Figure 10. 20 Day OBC Ephemeris Load Pointing Accuracy